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Dutch research on the impact of shield tunnelling on pile foundations

Recherche néerlandaise sur l'impact de tunneliers à bouclier sur fondations sur pieux

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ABSTRACT: In 1993 the Dutch government decided to commence with an extensive research and development program on underground construction. One of the main topics was to gather and develop knowledge in the field of the impact of shield tunnelling on buildings (i.e. pile foundations) situated in the vicinity of the bored tunnels. Several research projects were started in 1993 combined with the already planned tunnel projects, such as the Second Heinenoordtunnel, the Botlek railway tunnel and more recently the Sophia railway tunnel. This paper describes the results of the research projects and gives an evaluation of the impact of shield tunnelling on the bearing capacity of pile foundations and the ratio between surface settlements and pile settlements.

RESUME: En 1993, le gouvernement néerlandais a décidé de commencer un programme de recherche et développement extensif sur les constructions souterraines. Un des principaux sujets d'études a été de dresser et d'améliorer l'état des connaissances sur l'impact des tunneliers à bouclier sur les constructions fondées sur pieux et situées à proximité des tunnels. Plusieurs projets de recherche ont débuté en 1993 dans le cadre des projets tunneliers d'alors tels que le Deuxième tunnel d'Heinenoord, le tunnel ferroviaire du Botlek et plus récemment le tunnel ferroviaire de Sophia. Le papier décrit les résultats de ces projets de recherche et évalue l'impact du creusement à l'aide d'un tunnelier à bouclier sur la capacité portante des fondations sur pieux et le rapport entre le tassement à la surface du sol et celui des pieux.

1 INTRODUCTION

In 1993 the Dutch government decided to commence with an extensive research and development program on underground construction. One of the main topics was to gather and develop knowledge in the field of the impact of shield tunnelling on buildings (i.e. pile foundations) situated in the vicinity of the bored tunnels. Several research projects were started in 1993 combined with the already planned tunnel projects, such as the Second Heinenoordtunnel, the Botlek railway tunnel and more recently the Sophia railway tunnel. In these, so called, pilot projects special attention was paid to assess and understand the influence and effects of shield tunnelling on pile foundations. It should be emphasized that in the beginning of the nineties elaborated plans were made of bored tunnels in several Dutch city centers with historical buildings founded on wooden and concrete piles to improve the mobility. The large Dutch cities as Amsterdam and Rotterdam have been founded in very soft soils with high groundwater tables. The buildings and the infrastructure are founded on piled foundations. The length of the piles varies from 12 m till 30 m depending on the soil and loading conditions.

1.1 *Geocentrifuge research 1993*

The research on the impact of shield tunnelling on piled foundations started in 1993 with geo-centrifuge research on the settlement of a loaded pile group due to the passage of a shield tunnel. It appeared that large settlements had to be feared in case of moderate up to bad TBM performance (volume losses of 1 % to 3 % and more). The tests were being conducted at the geocentrifuge in Delft (Bezuijen and Schrier, 1994). The results of these geocentrifuge tests showed that the piles could subside more than 10 cm (roughly equaling a wooden pile toe diameter) for a combination of a substantial volume loss (approx. 3%) and a small distance between pile toe and tunnel. The conclusions based on these test results recommended a safe distance of two tunnel diameters between the TBM and the pile toes to avoid substantial subsidence and settlements.

Referring to the designs of bored tunnels in the historic cities the consequences of these conclusions could be that the construction of tunnels was hardly possible due to the financial matters. The tunnels would have to be excavated significantly deeper (due to the minimum distance of 2D) than initially was considered as desirable, both from a financial as well as a comfort point of view (very deep stations and tall escalators).

1.2 *North/South Line Amsterdam design (1994 –2001)*

In 1993 the Municipality of the city of Amsterdam decided to build a new metro line. The total length of the metro line in Amsterdam is 9.6 km. A major part of it (3.9 km) crosses the historic center of Amsterdam as two bored single track tunnels (6.5 m). The alignments of the metro line will pass nearby (within a distance of 20 m) more than 250.000 wooden and over 2000 concrete piles of the foundations of the adjacent buildings, see figure 1).

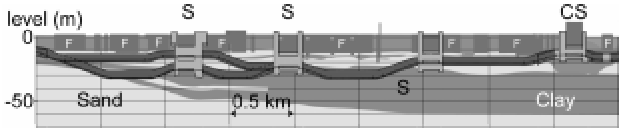

Figure 1. North South line bored tunnel alignment. S are the planned metro stations, CS is the existing train station and F indicates existing pile foundations adjacent to the trace.

At the early beginning of the design process, the research program on the influence of tunnelling on pile foundations was of vital importance for the design of the North/South metro line in Amsterdam. The metro is under construction at present (2001-2014).

A balance had to be found between reducing the depth of the stations to a minimum without increasing the risk of settlements along the adjoining tunnel stretches. The designers, however, felt that there was a possibility that the test results from the geocentrifuge were somewhat conservative due to the manner in which the tunnelling process was simulated. Based on experiences from international projects, it was expected that massive volume loss, which in turn could generate substantial pile toe stress relaxation, could be avoided.

In the early design stage of the North/South Line it was evident that the effect of tunnelling on the load bearing capacity of pile foundations was a yet to be discovered area of expertise. In particular the phenomenon of possible stress relieve effects around the pile toe that potentially cause extra substantial pile settlements has urged the North/South Line organization to initiate the first in a serie of full scale trials. These trials, conducted full-scale at the Second Heinenoordtunnel, formed the basis of an elaborated research program which ultimately, due to reduction of construction risks, earned to repay its initial investment. The Second Heinenoordtunnel was the first bored tunnel in the Netherlands and appointed as project at which pilot tests could be carried out. In 1996 it was decided to perform an extensive pile experiment at the Second Heinenoordtunnel (figure 2).

2 THE FULL SCALE PILE TEST AT SECOND HEINENOORDTUNNEL

2.1 *Second Heinenoordtunnel*

The Second Heinenoordtunnel consists of two tunnels with an outer diameter of 8.3 m which are bored with a center to center distance of 16.3 m (the distance between the tunnel lining is 1D = 8.3 m). The construction of this tunnel started in February 1997. The first crossing of the test site was in April 1997, the second crossing in the summer of 1998. The results of the tests could be incorporated in the detailed design of the North/South Line.

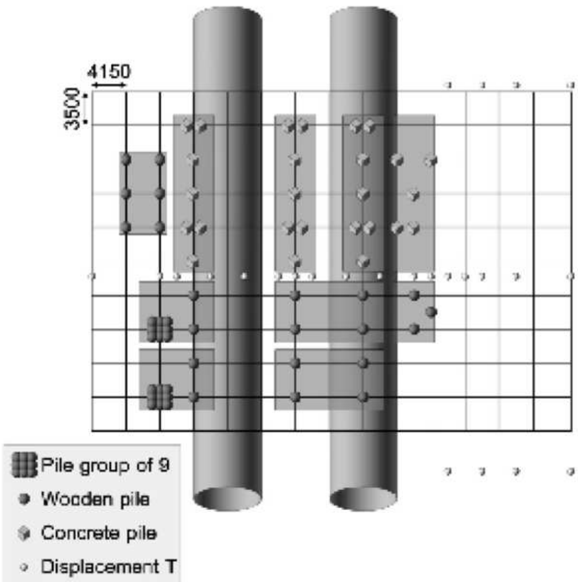

Figure 2. Overview test field with the 2 tunnel tubes. The left tube is drilled first. Numbers give the dimensions of the grid in mm. Gray areas are the loaded areas on the pile foundations. T stands for transducer

2.2 *Objective*

The test pile experiment for the North/South metro line had two main objectives:

1. To study the effects and risks of tunnelling near, beside and under pile foundations.
2. To validate the use of the 3D FEM Programme DIANA. This program was used in predicting pile and (sub) surface settlements.

The test results were used in the final design of the North/South metro line. The validated FEM program was used in optimizing the foreseen mitigating measures.

The deformation of a pile due to tunnelling consists of two different phenomena, as knowing:

1. settlement of the soil layer around the pile toe and
2. settlement caused by stress relieve all round the pile toe. In formula:

$$\delta\, Zpile_{toe} = \delta\, Z_{soillayer} + \delta\, Z_{stress\ relieve} \qquad (1)$$

2.3 *Key Question to stress relieve*

The wooden foundation piles in Amsterdam mainly carry their loads via the pile toes to the subsoil (80% end bearing). At the start of the design phase, one of the key-questions with respect to the design of the vertical alignment of the bored tunnels, was the quantification of the influence of bored tunnelling on the bearing capacity of the piles. There was some initial concern whether the piles would subside more than the surrounding subsoil at toe level, as stresses in the compressed zones around driven pile toes might drop if the distance between tunnelling and the foundations becomes too small (stress relieve at the pile toe). The Tunnel Boring Machine (TBM) generates a (minimal) volume loss, which theoretically could cause soil stress relieve. This phenomenon is called pile toe stress relaxation or stress relieve. There was hardly any knowledge of actual practise available on this design issue.

At the project North/South Line Amsterdam, the target figure for volume loss was, based on extensive Settlement Risk Assessment studies, already set at 0,5%, which had already lead to the development of a specific settlement minimizing TBM. (Kaalberg and Hentschel, 1999). The question that remained was: how closely to the piles the TBM can operate in this target operating modus without adverse consequences. It was expected that the effects of the pile toe stress relieve would be negligible from a distance of 1D if the volume loss stayed within 1%, which is generally considered as a good TBM (settlement) performance.

2.4 *Description Full Scale Pile Trials*

The soil conditions of the test site are different from Amsterdam. In Amsterdam the upper 10-12 meters consists of very soft silty clays, peat and loose sand deposits. Underneath these soft layers a sand layer is found (NAP -10 to -13m, NAP is Dutch Reference Level and is equal to mean sealevel). Most wooden piles are founded on this layer. At the test site only the first four meters consists of soft clay, then fine sand is deposited.

To stimulate the Amsterdam subsoil conditions large clay columns have been constructed. To validate the simulation the ratio between the toe bearing capacity and the shaft friction is an important input parameter. This ratio was set equal to the ratio of the piles in Amsterdam by reducing the shaft friction of the piles on the test site by use of the clay columns. CPTs and boring samples of the strength and deformation properties were quite similar to the top layer of Amsterdam. Subsequently the piles were rammed through the clay pile and founded in the sand layer. The pile loads are similar to most Amsterdam pile configurations.

In total 43 timber piles and 20 concrete piles were placed in the vicinity and above of the tunnel. The timber piles have been placed in a single position, a double position with a distance of 0,5 m and two pile groups of each 9 piles constructed. The pile groups of 9 piles simulate foundations of a big building and the configuration of 2 piles with a cross-beam a typical Amsterdam wooden pile foundation. The test field has the dimensions of 50 * 70 m^2 (see figure 2).

2.5 *First TBM Passage*

For the first passage, a total of 38 wooden and 18 concrete piles were installed and loaded at the northern bank of the river 'Oude Maas'. The pile toes were located at a distance of 0,5 D to 2,5 D from the tunnel tube (tube diameter D). The wooden piles in the Amsterdam configuration were loaded with concrete New Yersey barriers whilst the concrete piles and wooden pile groups were loaded by placing sand-filled containers on top. The vertical loads varied from 55 to 110 kN for the timber piles and from 330 kN to 950 kN for the concrete piles. The frames were designed to perform soil investigations through or between the loads and containers. An overview of the pile experiment test site is given in figure 3. Through a load-controlled jack, the weight of the load was transported to the piles, so each pile, at all times would receive a clearly measurable load (figure 3).

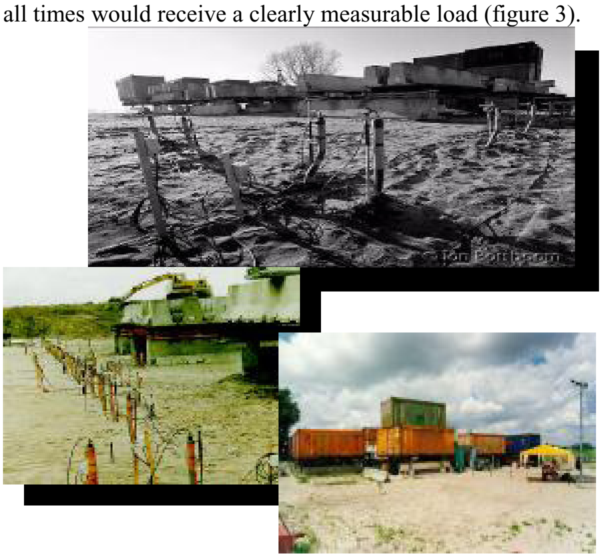

Figure 3. Impression of the location of the full scale pile trials

2.6 *3D FEM-research program*

The tests were supported with an ambitious 3D FEM research programme to calibrate and validate the FEM research models. The 3D-models were created to transfer the test results obtained from the Rotterdam subsoil, to the Amsterdam conditions. In addition, prediction results could be generated for other (more nearby located) configurations of tunnels and piles. The FEM program was considered to be highly ambitious because 3D staged calculations were used for the first time (1998) at this scale and, more particularly, also the penetrating effect of piles that were driven into the subsoil had to be modelled properly. If these installation effects had not been taken into account, the predictions would have been worthless since it was assumed that relaxation around the pile toe as the TBM passes was the main factor to be researched regarding the settlements of the piles. To obtain this initial position, individual penetration calculations, based on the Eulerian principle within GeoDelft's DIEKA program (Berg, 1994), were conducted by GeoDelft and validated with the results of static pile load tests.

The DIEKA calculations generated both load-settlement diagrams, as well as satisfactory initial strain distribution patterns in the sub soil along the pile shaft and pile toe. These 3D strains were subsequently implemented into the 3D DIANA-model after which the construction of the tunnel was simulated, in the same DIANA model whilst varying the volume loss.

The 3D predictions showed that even when allowing a smaller distance between the tunnel tube and the pile toes than were allowed during the trials, (up to 0.25 D) no substantial pile toe stress relaxation was to be expected. However, the models showed that it was possible that some redistribution of end bearing and shaft friction could occur.

3 MEASUREMENTS

3.1 *Field instrumentation*

The measurements were carried out by using a full automatically system based on the 'waterlevel method'. At each pile and surface point an accurate pressure sensor was fixed. The sensor is immersed in a pipe system filled with a liquid. The pipe system is connected with a fixed point. When a pile sets, the fixed sensor is more immersed. The sensor measures 200 times per minute and sends this data to a computer. The computer determines the average of every minute and stores the overall average of 20 minutes. So the monitoring is covered for the whole testing period of in total 2 years. Besides this every 4 hour during the passage of the TBM a precise leveling was carried out using total 9 stations. The accuracy of both measurements was within 0.2 mm.

To determine the effect of tunnelling on pile foundations three different and independent monitoring principles were used.

1. Pile, surface and sub surface settlement

The deformation of each pile was continuously monitored during the crossing of the TBM. Then the load was kept constant, using hydraulic jacks. In total 13 single timber piles, 20 single concrete piles, 6 blocks of double timber piles and 2 blocks of 9 timber piles were installed and monitored.

Also 90 surface points were monitored and these are placed in three arrays with a width of 60 m perpendicular to tunnel axis and two arrays parallel and direct above the tunnel axis. The horizontal displacements parallel and perpendicular to tunnel axis were monitored at one array. Additional to the surface points, 29 extensometers varying for NAP tot NAP –28 m were monitored. In three piles and at 8 locations in the field inclinometer tubes (some at 0.5 m from the tunnel tube) were installed to monitor the horizontal deformations. Before, during and after the passage of the tunnel boring machine, data has been registrated as follows:

- vertical pile deformations;
- pile and subsoil deflections and pile loads;
- vertical surface and sub surface settlements;
- horizontal surface deformations;
- 7 SMS stations (Stress Monitoring System) installed in the pile toes;
- 12 SMS in the sub surface.

2. Static pile load tests

Static pile load tests were performed on 4 piles (two piles timber and two concrete piles) before and after the first tunnelling track. The effect of tunnelling was obtained by comparing the ultimate bearing capacities before and after passage of the TBM.

3. Soil investigation

The effects of tunnelling on pile foundations also have been measured and interpreted based on soil investigations, which was carried out in four stages:

1. before pile driving: this stage was used for the detailed of the pile experiment;

2. just before passing the first bored track, after installation of the test loads;
3. after passing the first bored track;
4. after passing the second bored track.

The soil investigation consisted of 68 CPTs, one boring and several laboratory tests, two dilatometer tests and 8 Cone Pressiometer tests (CPM in stage 2 and 3). By comparing the CPTs and CPMs in stage 2 and 3 the stress relieve, stiffness reduction of the soil, relaxation of the pile load displacement due to tunnelling has been obtained.

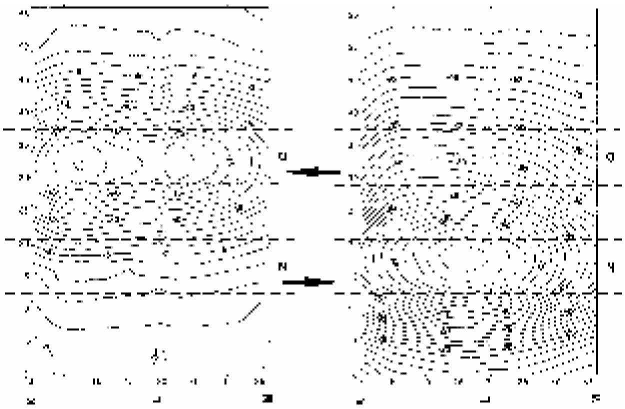

Figure 4. Measured settlements after second passage(left) and total settlement, after first and second (right).

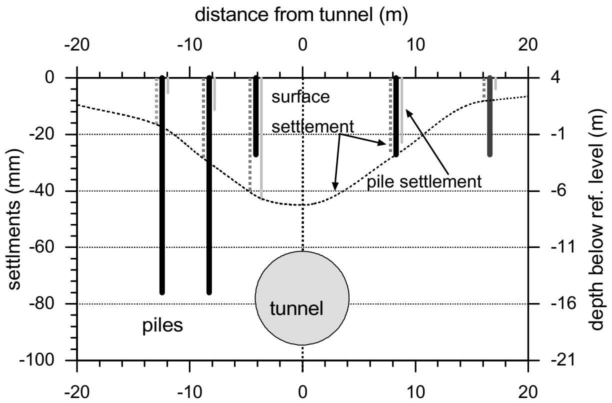

Figure 5. Measured settlement pile v.s. surface settlements, first passage

3.2 *TBM instrumentation*

Besides above mentioned measurements the TBM was also equipped with instruments to study the stability of the bore front, excavation and mixture formation, the balance of forces and the effectiveness. For this purpose, 16 pressure sensors were installed at each hydraulic jack and sensors for velocity and rotation measurement of the TBM and at the transportation systems (pumps and pipelines).

Combining the results of the pile and surface settlements with the measurements of the TBM, correlation between volume loss, effectiveness and settlements were derived.

4 RESULTS TRIAL SITE

4.1 *First TBM passage*

When the TBM passed the test site for the first time (at a distance of minimal 0.5 D) the settlement of the surface was fairly substantial, up to 45 mm and volume losses at surface between 1.0 and 2.0 % (figure 4). Based on the results of the centrifuge tests (Bezuijen and Schrier, 1994) the assumption could be made that relaxation would have occurred in the subsoil. In spite of this, the alleged stress reduction around the pile toes did not have an effect on the behaviour of the piles. This could easily be derived from the comparison between the measured surface settlements and pile head settlements, which at maximum equal the surface settlement (figure 5). Additionally, the TBM performance results were established on the first couple of hundred metres of bored tunnelling in Dutch soil. It was expected that the quality of the tunnelling process could be further optimised in the second passage of the trial area. Since the FEM-model predicted little effect at even smaller distances, (to 0.25D), another 7 piles were driven for the second passage of the TBM. All the piles, even the timber piles, were instrumented with Stress Monitoring Stations (SMS) and piezometers.

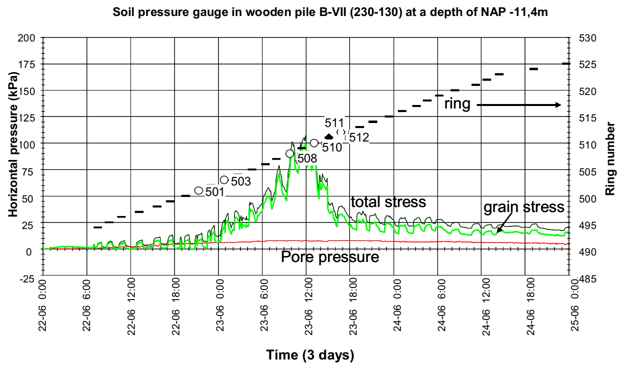

Figure 6. Measured changes in total stress, water pressure and resulting effective stress at pile side during TBM-passage.

The distance between the tunnel and the pile toes was now further reduced to from 0.5 D to 0.175 D. This time, in addition 23 extensometers, inclinometers and 12 SMS (in 2 directions) were placed into the sub-soil. Figure 6 shows that the horizontal effective stress at the pile shaft derived from the SMS and piezometer measurements increases during TBM-passage at a distance of 0.25 D form this pile.

4.2 *Second TBM Passage*

The second passage of the TBM generated much smaller settlement contours at surface level (figure 4), which, after a post analysis was mostly contributed by the improved grout injections into the tail void between the tunnel lining and the TBM (the back calculated volume loss at surface was approx. 0.75%).

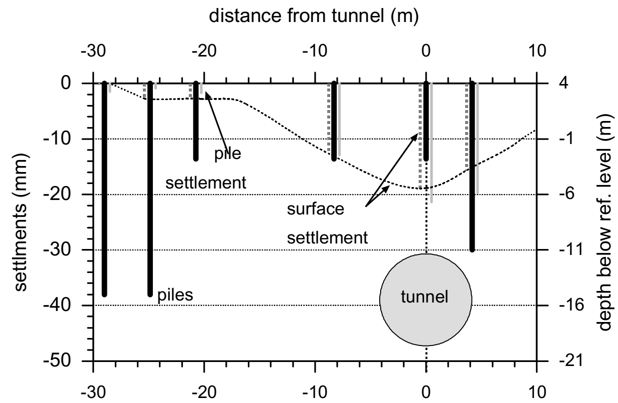

Figure 7. Measured settlement pile v.s. surface settlements, second passage

Figure 7 shows clearly that the piles with the toe close to the tunnel suffer larger settlements then the surface settlement during the second passage at. Also the pile toe stress relaxation had reached its optimum, since at a distance of 0.25 D, a certain -but not substantial- effect was measurable (given the minimal loss of volume). This was derived from a combination of results from pile toe data, the sub surface settlement data (extensometers) and the stress contours, generated by means of SMS. (figure 8 and en 9). It also became clear that the surface settlement contour was much steeper, see figure 10 than was predicted with the contraction models which had formed the basis of both tests in the centrifuge as well as the 3D FEM tests. The tunnelling process had up to this moment only been simulated with the principle of concentric volume loss, which appeared to be conservative since the actual grout pressure distribution in the tail void of the TBM was not taken into account. Moreover the deformations appeared to occur nearly instantaneous during the passing TBM.

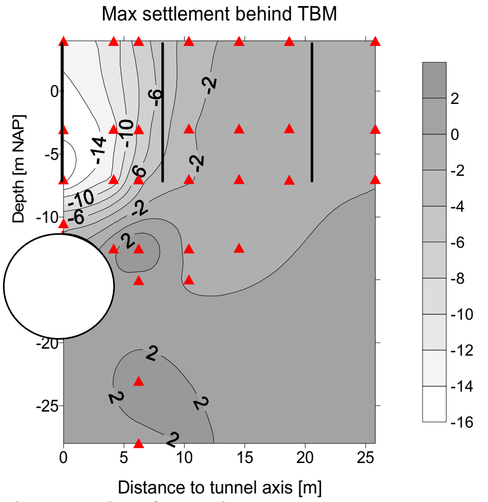

Figure 8. Sub surface settlement contour

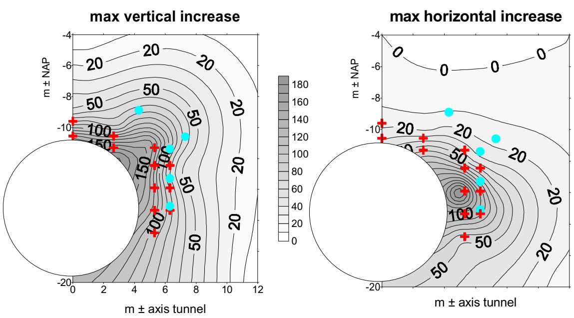

Figure 9. Stress changes after second passage TBM

Figure 10 shows that 80% of the surface settlement occurs within two days. Both phenomena are unfavourable for the adjacent buildings as steep settlement contours result in high relative rotations perpendicular to the tunnel axis and the rate of the settling process causes high rotations along the tunnel axis.

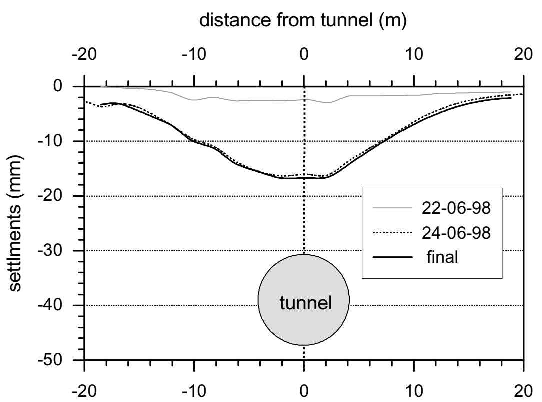

Figure 10. Measured surface settlement. 80% of the surface settlement occurs within two days

As said above, three independent measurements were carried out to determine the effect of tunnelling on the pile deformations and the occurrence of stress relieve at the pile toe. Besides the continuously pile, surface and sub surface settlements results also CPTs and load tests were carried out.

4.3 *CPT tests*

To examine how the passing TBM influences the pile bearing capacity, CPT tests are performed.

In figure 11 the results of CPT tests (0.35 meters beside the tunnel line) are presented.

The CPTs before and after the passage of the TBM show no significant changes. Hence assuming a direct relation between cone resistance and pile capacity confirms that tunnel boring near pile foundations does not affect the bearing capacity of the piles (the calculated bearing capacity based on the two different CPTs match). It can also be concluded that there is no significant stress relief near the pile toe.

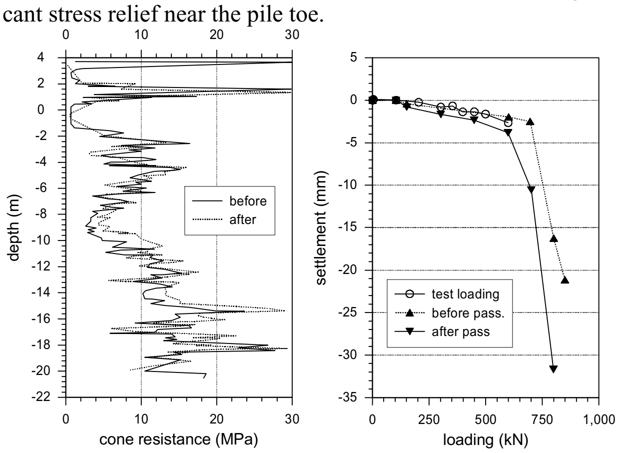

Figure 11. CPT before and after passage TBM, at 3.5 m distance (left). Static pile load tests before and after passage TBM (right).

4.4 *Static ultimate bearing tests*

In addition, static pile load tests were performed and compared before and after the passage of the TBM: no significant differences were found either. (figure 11).

5 CONCLUSIONS OF THE EFFECTS OF TUNNELLING ON PILE FOUNDATIONS

5.1 *Conclusions of the effects of tunnelling on pile foundations*

With regards to the geometrical position of the piles in relation to the tunnel, the following general conclusions were drawn (figure 12):

Piles with toes founded in zone A undergo a pile toe deformation minimally equal or slightly larger to the surface-level subsidence on a corresponding location.

Piles with toes founded in zone B generally about equal the surface-level subsidence.

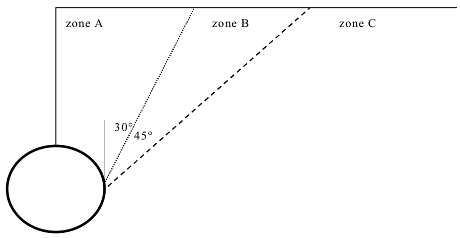

Figure 12. Pile toe influence zone

With respect to the deformation of the piles founded in Zone C, the pile subsidence is significantly smaller than the corresponding deformation of the ground level.

Based on all the results of both of the passage and comparing the results with the 3 FEM predictions the following conclusions were made:

- The inclination of the settlement trough, both in longitudinal as in perpendicular direction is steeper than was expected and predicted. This means that the influence area is smaller than predicted, but the risks for nearby foundations will be larger. The steep settlement contours result in high relative rotations perpendicular to the tunnel axis and the high rate of the settlements results in a steep longitudinal trough causing high rotations along the tunnel axis.
- The volume loss over the field, measured at the surface, is not constant but varies from 1.0 to 2.0 % at the first passage. Post dictions to calibrate the predictions to the measurements lead to an input parameter of the volume loss at the TBM of about 2 to 3 %.
- During the second passage the 'volume loss' measured at the surface was much more in control and was approximatly 0.75 %.
- Stress relieve due to tunnelling is almost negligible. Both the results of prediction and measurements, CPTs and bearing tests lead to this conclusion.
- Time depended settlements of piles and surface are about 15% of the settlements immediately after TBM passage.

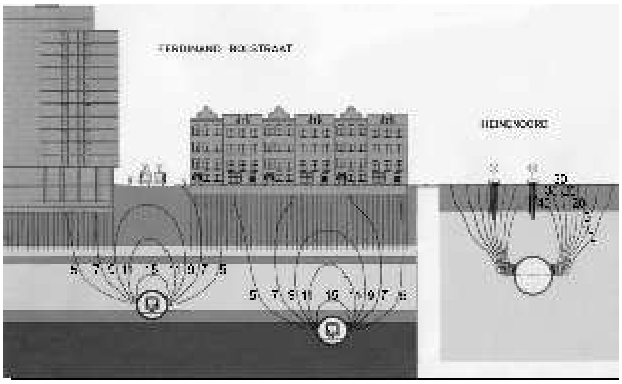

Figure 13. Translation pile experiment to North South Line. Numbers for "Heinenoord" show the pile settlement estimated based on the experiments described here. Numbers for "Ferdinand Bolstraat" are a prediction for the Amsterdam Metro.

5.2 *Translating the trial results to Amsterdam*

Based on above mentioned results, 0.5 D was considered for future reference, a safe distance between piles and tunnels (taking a certain margin for varying volume loss into consideration). The initial expectations with regards to the phenomenon of pile toe stress relaxation were hereby confirmed and the initial starting points in the design of the vertical alignment and deep-stations were maintained. After the tests, the steeper sub surface settlement contours could be calibrated with a renewed 4D-model. The differentiated radial grout pressure distribution in the ring-shaped tail gap around the tunnel, a detailed propagating TBM and a ring-shaped tunnel lining are now taken into account (Dijk & Kaalberg, 1998).

These prediction results were used in the stage II settlement risk assessment studies, which showed that the damage risk expectation for the adjacent objects could be reduced. In the currently running phase III, the 4D grouted pressure model will be further developed.

5.3 *Overall Conclusion*

The set-up of a trial test at the Second Heinenoordtunnel (63 loaded piles, 90 surface points, 29 sub surface points, 12 SMS, 11 inclinometers, 7 piles instrumented with piezometers and SMS were continuously measured during almost 2 years, including the TBM instrumentation) towards the influence on piles and pile toes, was a daring investment which formed the basis for a structured application of the 'Design by Testing' philosophy (Kaalberg & Bosch, 2002) during the design of the North/South Line and all other new to build bored tunnels in soft soil and in-between pile foundations. The test was an great success because its results supported the costs reduction in the design of the North/South Line. This reduction in costs was many times greater than the investments and, in turn, facilitated an easier assessment in favour of conducting following trials.

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